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Review

Battery equalization active methods

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HIGHLIGHTS

- A final table that summarizes, compares the main active balancing methods, and evaluates them is given.
- The methods operation principle (with pros/cons) is exposed for research and commercial purpose.
- The main parameters that affect the operation are identified, including the main equations.

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ABSTRACT

Many different battery technologies are available for the applications which need energy storage. New researches are being focused on Lithium-based batteries, since they are becoming the most viable option for portable energy storage applications. As most of the applications need series battery strings to meet voltage requirements, battery imbalance is an important matter to be taken into account, since it leads the individual battery voltages to drift apart over time, and premature cells degradation, safety hazards, and capacity reduction will occur. A large number of battery equalization methods can be found, which present different advantages/disadvantages and are suitable for different applications. The present paper presents a summary, comparison and evaluation of the different active battery equalization methods, providing a table that compares them, which is helpful to select the suitable equalization method depending on the application. By applying the same weight to the different parameters of comparison, switch capacitor and double-tiered switching capacitor have the highest ratio. Cell bypass methods are cheap and cell to cell ones are efficient. Cell to pack, pack to cell and cell to pack to cell methods present a higher cost, size, and control complexity, but relatively low voltage and current stress in high-power applications.

1. Introduction

Along the last years, the research on electric vehicles has become of special interest due to the environmental awareness (which leads to autoemission standards getting stricter to follow, more efficient transportation vehicles, Government incentives, etc.), the continuous increase of the oil price because of the natural resource exhaustion and the instability in the Middle East, etc.

Hybrid Electric Vehicles (HEVs) were the first proposed solution to the trend toward more electric vehicles [1], and nowadays EVs (electric vehicles) are coming out more and more [2].

Different battery technologies have been studied and utilized for the EVs, but new researches are developing the Lithium-based batteries which are becoming the most viable option for portable and mobile energy storage applications, especially for EVs [3–13].

Most of applications for batteries need a higher voltage than the one that can be obtained from a single electrochemical battery and series strings of batteries are used to meet voltage requirements in EVs [14–21].

Imbalance of cells (each battery that makes up the whole battery pack is called cell hereafter unless otherwise noted) in battery systems is very usual and an important matter in the battery system life [22–25]. It is caused by two major categories [26–28], they are the internal sources that consist of manufacturing variance in physical volume, variations in internal impedance and differences in self-discharge rate; and external sources such as thermal difference across the pack. A battery system without a balancing technique takes special importance in Li-based cells [29–31], since it can lead its cells to be overcharged, undercharged, or even overdischarged [32].

Imbalance harms performance can be summarized in four different groups [33]. The first group deals with premature cells

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degradation due to the overvoltage exposure. The effects of the cell degradation caused by imbalance is auto-accelerating, once a cell has a lower capacity, it is exposed to an increasingly higher voltage during charge, what makes it degrade faster, and so its capacity becomes even less, closing the runaway circle. The second group is safety hazards from overcharged cells. Overcharging and overheating of the battery lead to a reaction of the active components with electrolyte and with each other ultimately, inducing explosion and fire. Thermal run-away can be caused merely by overcharging a single cell to voltages above 4.35 V [33]. Other cells of the pack will also join the explosive chain reaction if one cell is compromised. The third group is based on the early charge termination resulting in reduced capacity. The charging process is finished if one of the cell voltages exceeds the programmable cell overvoltage threshold due to safety reasons. Finally, the last and forth group deals with early discharge termination. In order to prevent the overdischarge of the cells and resulting damage, the discharge process is finished if any of the cells reaches the low voltage threshold.

Based on the cited problems, the equalization for the Lithium-based series-connected battery string is necessary in order to mainly keep the energy of the cells balanced and extend their lifetime [34–39].

Along this paper an overview of the battery equalization methods is presented, which is focused on active methods as these are the most efficient ones. In Section 2, they are organized into the three main groups. Since only active methods are efficient, Section 3 is focused on active equalization methods, in which a brief description of each method is outlined. Finally Section 3.6 presents a table that summarizes and compares all the methods introduced in the previous section. In Section 4 conclusions are highlighted.

2. Balancing methods

Balancing methods can be divided into three main groups: battery selection (building the battery pack by selecting the cells with similar properties), passive methods (no active control is used to balance) and active methods (external circuitry with active control is used to balance), as shown in Fig. 1.

It has to be mentioned that along the schematics of the different topologies shown in the different figures, I_{charger} is the charging ($I_{\text{charger}} > 0$) and the discharging ($I_{\text{charger}} < 0$) source current.

2.1. Battery selection

By properly selecting cells so that their properties are uniform (similar electrochemical characteristics) [40,41] in order to make up the battery pack, the issues of voltage imbalance can be mitigated.

Two different screening processes are carried out to select the similar cells. The first one obtains the cells with similar average capacity by discharging at different current regimes. It is based on

$$C_{\text{Cell}_i} = \int_{t_{\text{SOC}=0\%}}^{t_{\text{SOC}=100\%}} I_{\text{Cell}_i} \text{d}t, \quad (1)$$

where C_{Cell_i} is the cell capacity defined as the maximum electrical charge (Ah) that the cell can deliver from the fully charged state to the fully discharged state, I_{Cell_i} is the cell current, and $t_{\text{SOC}=100\%}$ and $t_{\text{SOC}=0\%}$ are the State of Charge of the cell at the fully charged and discharged states, respectively.

The second screening process is applied to the cells selected in the first one. Pulse type discharging/charging currents are applied for different SOC points to select the cells with similar voltage variance (similar series resistance associated with the cell).

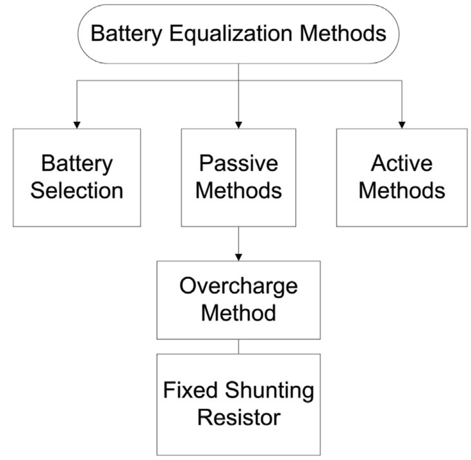

Fig. 1. Classification of the battery equalization methods.

This method is not enough to keep the series string balanced since their self-discharge can vary differently along their lifetime [42]. It can only be useful in case of complementing a balancing system.

2.2. Passive methods

No active control is used to balance. Passive methods can only be used for Lead-acid and Nickel-based batteries as Li-ion batteries cannot be overcharged.

They can be subdivided into two subgroups: overcharge and fixed shunting resistor.

In the overcharge method, when cells are fully charged, due to internal reactions cells stop being charged and the energy is converted into heat rather than stored. It is only effective on a small number of series cells as balancing problems grow exponentially with the number of series cells [5,29,43,44]. It cannot be

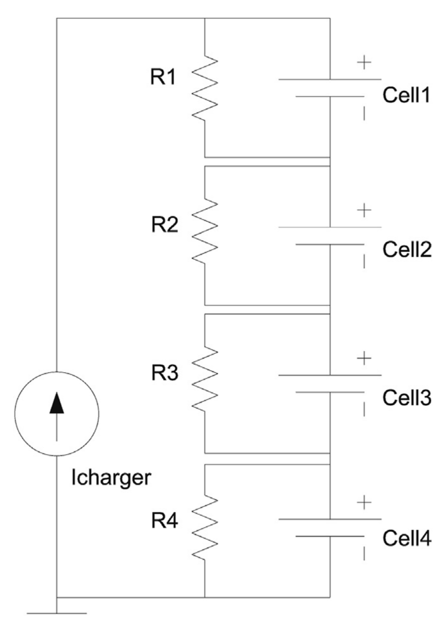

Fig. 2. Fixed shunting resistor method.

repeated forever without eventual damage of the battery, since the side reactions and the loss of water degrades the performance and life of the unit. The fixed shunting resistor method [45,46] uses a resistor in parallel with each individual cell in the pack, as shown in Fig. 2, and the current is partially or totally bypassed from the cells in order to limit the cells voltages. This method is continuously bypassing current and therefore continuously wasting energy.

2.3. Active methods

Active balancing methods use external circuits to actively transport the energy among cells in order to balance them, and are the only ones that can be implemented for Lithium-based batteries [43,46–50]. Only the basic methods are presented in Section 3, although there are variations that can optimize the equalization process by adding new components or modularizing [27,51].

3. Active methods

Attending to the energy flow, active balancing methods can be grouped into five categories: *cell bypass*, *cell to cell*, *cell to pack*, *pack to cell* and *cell(s) to pack to cell(s)*.

A diagram of the different active balancing methods is shown in Fig. 3.

In *cell bypass* methods, cells currents are bypassed when the cells voltages reach their upper limit. *Cell to cell* methods transfer the extra energy stored in the most charged cells to the adjacent least charged ones. *Cell to pack* methods transfer the energy from the highest voltage cell to the whole battery pack, *pack to cell* methods transfer the energy from the whole battery pack to a single cell, by means of galvanic isolated DC/DC converters, and finally, *cell to pack to cell* methods transfer the energy from the set cell(s) to the whole pack, from the whole pack to the target cell(s) or from the set cell(s) to the target cell(s).

3.1. Cell bypass

Three groups subdivide this method: complete shunting method, shunt resistor, and shunt transistor methods.

3.1.1. Complete shunting

Each individual cell is individually controlled by only using two power switches (or bidirectional switches, attending to the utilized topology) [52–55], as shown in Fig. 4. Each cell is fully shunted, that is to say, it is disconnected from the current path, when either it reaches its maximum voltage (minimum in discharge mode) or it is close to a reference value, depending on the control strategy. The advantages of this method are the relatively low cost and high efficiency. It is easy to be modularized. The main disadvantage is that it can only be used for low power applications since the higher the currents through the switches are or the number of cells is (the higher the voltage of the whole battery pack is), the less the efficiency is because of the switches on-resistance, and the efficiency degradation per cell follows

$$\Delta\eta = -\frac{Rl_{\mathrm{sw}}I}{NV_{\mathrm{cell}}}, \tag{2}$$

where $\Delta\eta$ is the efficiency degradation, R_{sw} is the on-resistance of the module bypass switch, I is the current, N is the number of cells, and V_{Cell} is the cell voltage.

3.1.2. Shunt resistor

A switch in series with a resistor is set in parallel with each individual cell in the battery pack [32,39,56–58], as shown in Fig. 5. The switches are controlled in two different modes: in the first mode, all of them are commanded by the same signal, that is to say, they all are set either *on* or *off* at the same time. In the second mode, cells voltages are monitored and each switch is commanded individually, so when the imbalance conditions are sensed, it is decided

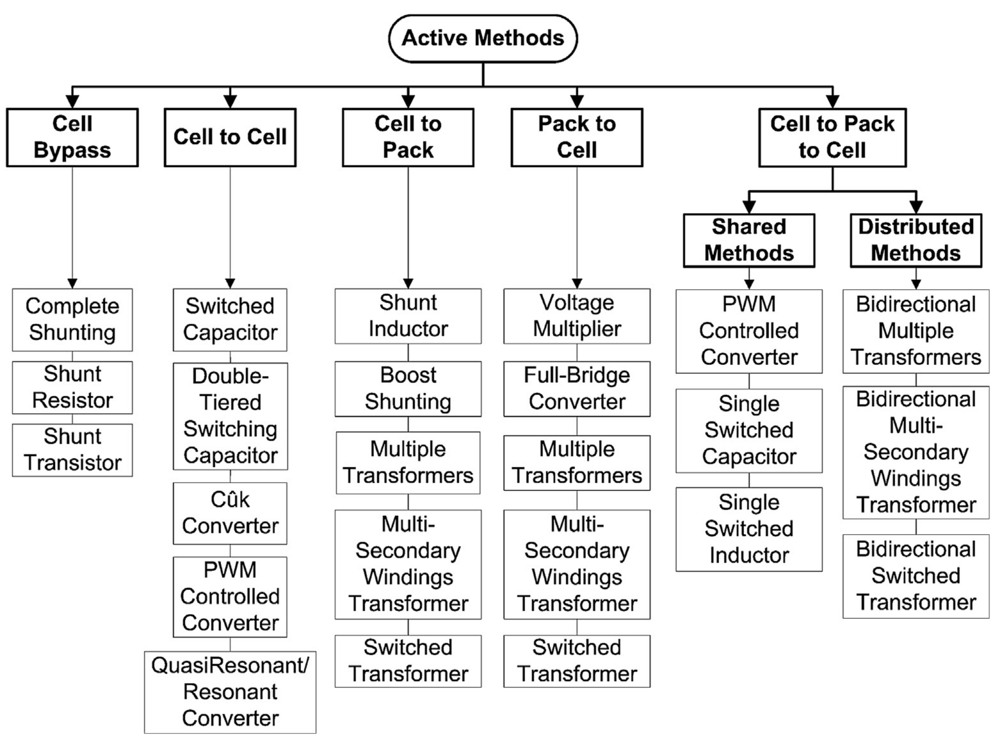

Fig. 3. Classification of the different active balancing methods.

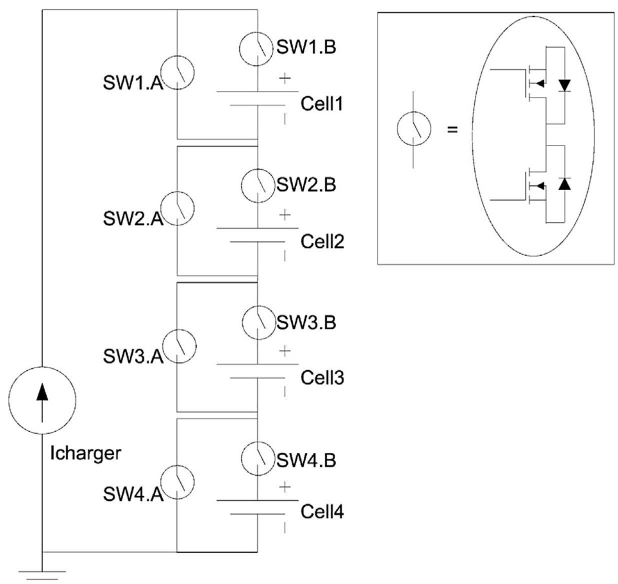

Fig. 4. Complete shunting method.

which resistor is shunted and a fraction of the current bypasses the cell (cells can be balanced during both charge and discharge modes). When a cell is bypassed, the current through the cell is

$$I_{\mathrm{cell}} = I_{\mathrm{charger}} - \frac{V_{\mathrm{cell}}}{R + R_{\mathrm{sw}}}, \tag{3}$$

where I_{Cell} is the current through the cell, I_{charger} is the current delivered by the charger, V_{Cell} is the cell voltage, R is the resistor set in parallel with the cell, and R_{sw} is the resistance associated with the switch.

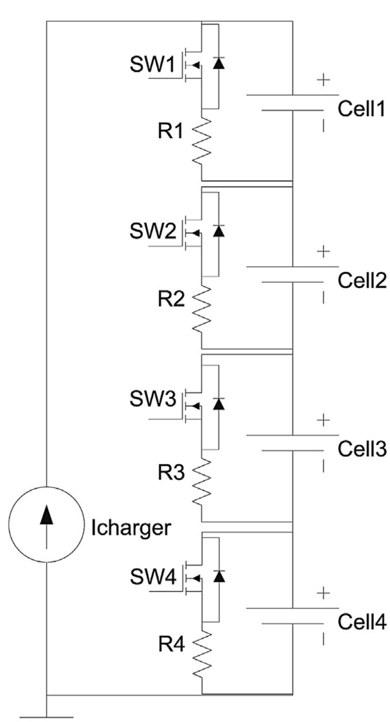

Fig. 5. Shunt resistor method.

The efficiency degradation per cell follows

$$\Delta\eta = -\frac{V_{\mathrm{cell}}^2}{R + R_{\mathrm{sw}}}. \tag{4}$$

The advantages of this method are the low cost and easy implementation. The main disadvantage is that it can only be utilized for low power applications as it has an excessive power dissipation and therefore a low efficiency operation.

3.1.3. Shunt transistor

It shares the same idea as the shunt resistor method. A transistor is set in parallel with each individual cell [56,58–61], as shown in Fig. 6. During charging, when the cell reaches the maximum voltage, the current is proportionally bypassed around the cell and so this cell is charged at constant voltage. In this method, the current is only shunted at the end of the charging process, so compared to shunt resistor working in the first mode, it has less energy loss. Compared to shunt resistor working in the second mode, it does not need intelligent control, and therefore the cost is lower. By considering $R_{\mathrm{sw}} = 0$, and R the transistor on-resistance, (3) and (4) can be applied to this method.

3.2. Cell to cell

This method can be subdivided into five methods, the switched capacitor, the *double-tiered switching capacitor*, the Cûk converter, the PWM (Pulse Width Modulation) controlled converter and the QuasiResonant and the resonant converter ones.

3.2.1. Switched capacitor

In this method, two states are alternated continuously. In the first state, each capacitor is set in parallel with its corresponding upper cell, and therefore the capacitor is set to the cell voltage, delivering or demanding energy from the mentioned cell. Once each capacitor has reached its corresponding upper cell voltage (V_{u_i}), the stored charge (Q_{c_i}) for the i-capacitor is

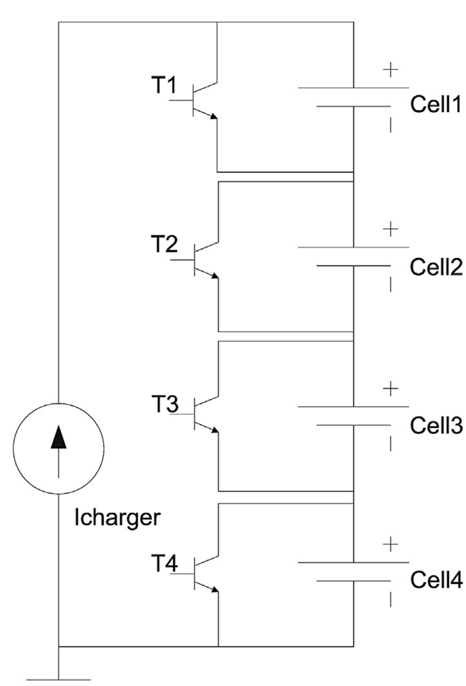

Fig. 6. Shunt transistor method.

$$Q_{c_i} = C_i V_{u_i}, \tag{5}$$

where C_i is the capacitance of the i-capacitor.

In the second state, the capacitors are set in parallel with their corresponding lower cell, transferring or demanding energy from this one in order to reach this new voltage. After cycles of this process, both cells will be balanced [28,62–68]. The topology is depicted in Fig. 7.

Each switching cycle, the i-capacitor transfers the current I_{c_i} from the most charged adjacent cell to the least charged adjacent cell according to

$$I_{c_i} = C_i (V_{u_i} - V_{l_i}) f_{sw}, \tag{6}$$

where V_{l_i} is the lower cell voltage of the i-capacitor and f_{sw} is the switching frequency.

Therefore the capacitor behaves like a resistance and the equivalent resistance R_c is

$$R_c = \frac{V_{u_i} - V_{l_i}}{I_i} = \frac{1}{f_{sw} C_i}. \tag{7}$$

By taking into account the on-resistance of the switches (R_{sw}), the total resistance for the i-capacitor (R_{sw_i}) is

$$R_{sw_i} = \frac{1}{f_{sw} C_i} + 2\frac{R_{sw}}{D}, \tag{8}$$

where D is the duty cycle.

The efficiency degradation per capacitor follows

$$\Delta\eta = -\frac{(V_{u_i} - V_{l_i})^2}{R_{sw_i}}. \tag{9}$$

The main advantages of this method are the efficiency, low complexity and the possibility of low and high power applications. No sensing or closed-loop control are needed. The main disadvantage is the speed, as the lower the voltage difference between adjacent cells is, the lower the balancing current is, and therefore the lower the balancing speed is.

3.2.2. Double-tiered switching capacitor

This method is a derivation of the switched capacitor one, the difference is that it uses two capacitor tiers for shuttling energy [69,70] and the equalization time is reduced even to a quarter. Fig. 8 shows the mentioned topology. Similar advantages and disadvantages are obtained compared with the switched capacitor method, Section. 3.2.1. The advantages compared with the switched capacitor are the balancing time and the lower balancing capacitors currents while simultaneously transferring more charge along the string of cells. It is due to a better charge distribution between the most charged cells and the least charged ones. The disadvantages are higher cost and size.

Its equations are analyzed in Ref. [71], which are not presented in this overview because of their extension.

3.2.3. Cûk converter

Each two neighbored cells are connected to an equalization module that allows the energy transfer from the cell with the highest voltage to the cell with the lowest one through the energy-transferring capacitor [18,72–75]. The topology of this method is shown in Fig. 9. The circuit is driven by PWM signals. By focusing on the Cell1 and Cell2 (the same ideas can be applied to the rest of pairs of adjacent cells), and considering that the Cell1 voltage is higher than the one of the Cell2, two steps are carried out to transfer the energy from the Cell1 to the Cell2 in order to balance: along the first period, the switches SW12 and SW21 are turned off and on, respectively. The current from the Cell1 (I_{L1}) charges the capacitor C12. Along the second period, the switches SW12 and SW21 are turned *on* and *off*, respectively, and the capacitor energy is transferred to Cell2.

The average currents for the inductors L1 and L2 are

$$I_{L1} = \frac{\frac{1}{2}\left(\frac{V_{Cell1}}{L1}D^2 + \frac{V_{Cell1} - V_{C12}}{L1}(1-D)^2\right)}{f_{sw}}, \tag{10}$$

and

$$I_{L2} = \frac{\frac{1}{2}\left(\frac{V_{Cell2} - V_{C12}}{L2}D^2 + \frac{V_{Cell2}}{L2}(1-D)^2\right)}{f_{sw}}, \tag{11}$$

respectively, where V_{Cell1} and V_{Cell2} are the Cell1 and Cell2 voltages, L1 and L2 are the inductors set in parallel with the Cell1 and Cell2, respectively, D is the switching duty cycle, and f_{sw} is the switching frequency.

Attending to (10) and (11), it can be deduced that ideally the higher the switching frequency is, the lower the balancing currents I_{L1} and I_{L2} are, and therefore the lower the losses of the associated resistances are, and in consequence the higher the efficiency is.

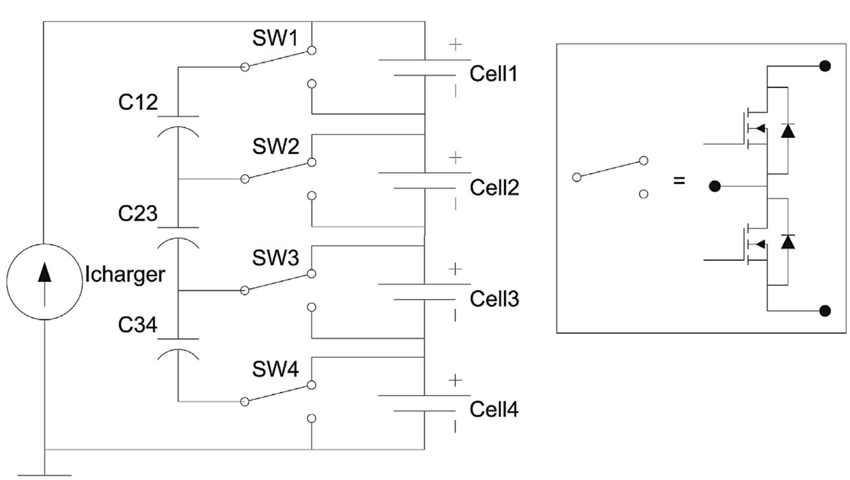

Fig. 7. Switched capacitor method.

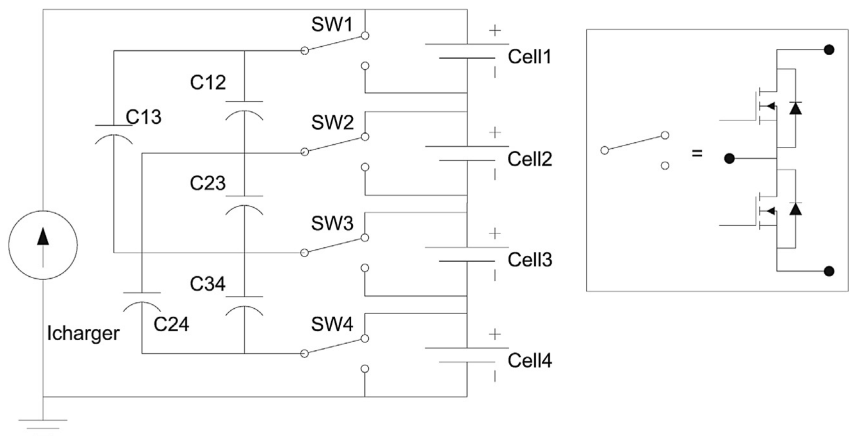

Fig. 8. *Double-tiered switching capacitor* method.

The main advantage of this method is that it can be utilized in high power applications, but its main disadvantage is its control complexity.

3.2.4. PWM controlled converter

Three different topologies can be implemented [76]. The basic topology is shown in Fig. 10. Every module for equalization is connected across each two adjacent cells to allow next-to-next energy transfer from the cell with the highest voltage to the cell with the lowest voltage. The energy is firstly transferred from the highest voltage cell to the inductance where it is stored, and then the inductance discharges the energy to the lowest voltage cell. The proposed circuit is derived from the buck–boost converter. The energy transfer and the flow direction are carried out by adjusting the duty cycle of the corresponding transistors, which are activated with a PWM signal [77–86].

Taking into account the inductance losses (R_L) and the switch losses (conduction loss (R_{sw})), the power losses per every pair of cells follow

$$P_{loss} = I_L^2 R_{sw} + I_L^2 R_L, \tag{12}$$

where P_{loss} is the total power loss, f_{sw} is the switching frequency, and $I_{L_{i,i+1}}$ is the average balancing current for the pair Cell$_i$–Cell$_{i+1}$ that can be calculated as

$$I_{L_{i,i+1}} = \frac{1}{2}\left(\frac{V_{Cell_i}D^2 - V_{Cell_{i+1}}(1-D)^2}{L_{i,i+1}f_{sw}}\right), \tag{13}$$

where D is the switching duty cycle, V_{Cell_i} and $V_{Cell_{i+1}}$ are the cell voltages of the Cell$_i$ and the Cell$_{i+1}$, and $L_{i,i+1}$ is the inductor between them.

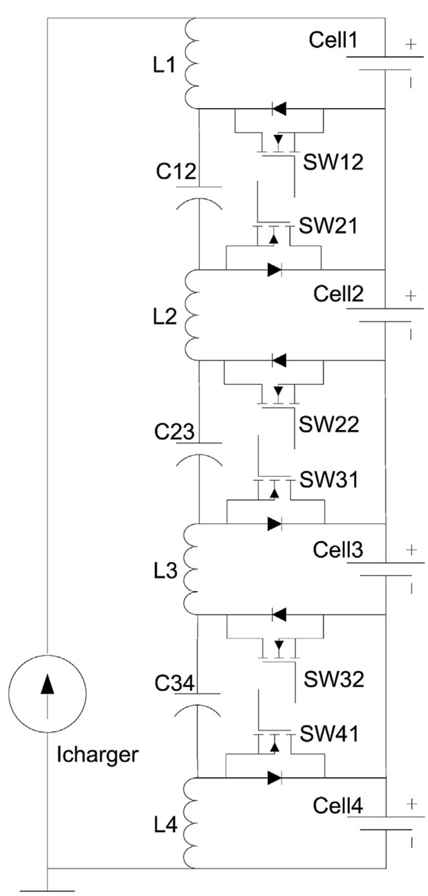

Fig. 9. Cûk converter method.

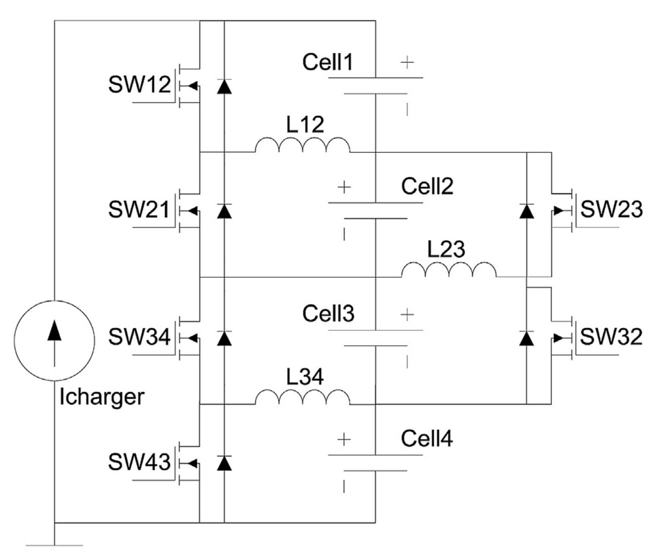

Fig. 10. *Cell to cell* PWM controlled converter method.

This method is good for high power applications, but its control complexity.

There are proposed variations that optimize the balancing such as [87], which uses a capacitor in parallel with every pair of switches, or [88] which allows to transfer the energy between non-adjacent cells.

3.2.5. QuasiResonant/resonant converter

Both the QuasiResonant converter and the resonant converter methods are similar to the PWM Controlled Shunting method [89].

The QuasiResonant converter topology is shown in Fig. 11. Each pair of balancing module switches is commanded by a PWM signal, as in the PWM Controlled Shunting. The difference is that instead of using an inductor, a resonant circuit is utilized to transfer the energy between the neighbored cells, achieving the zero current switching function for the symmetrical and bi-directional battery equalizer. This topology allows a reduction of the switching losses and EMI (Electromagnetic Interference) emission of the battery equalizers [90–92]. Some modifications can be carried out in order to obtain Zero Voltage (ZVT) Zero Current (ZCT) Transitions [89]. ZVT technique eliminates the capacitive turn-on loss, and reduces the turn-off switching loss as it slows down the voltage rise and reduces the overlap between the switch voltage and the switch current. ZCT technique eliminates the voltage and current overlap by forcing the switch current to zero before the switch voltage rises [93].

Equations are not presented in this overview due to their extension.

In the resonant converter, instead of using intelligent control to monitor and generate the switches PWM signals, a resonance circuit is used for each equalization module which both transfers the energy and commands the switches using a zero voltage–zero current transition converter [94]. A start-up circuit is needed to start the resonance.

This method is good for high power applications, but its main disadvantage is its high control complexity.

3.3. Cell to pack

This method can be subdivided into five methods: the shunt inductor, boost shunting, multiple transformers, multisecondary windings transformer, and switched transformer ones.

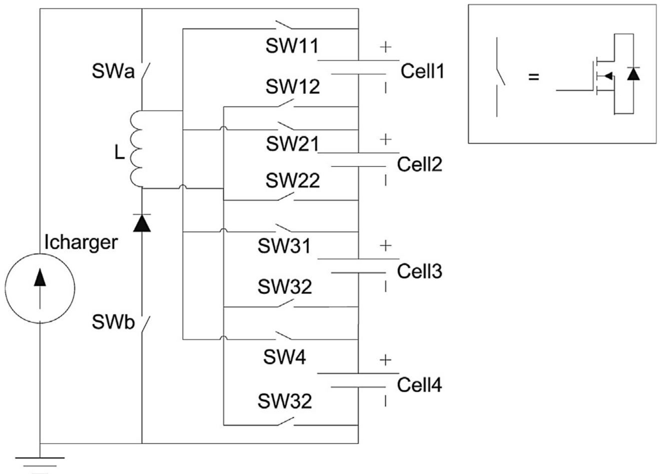

Fig. 12. Shunt inductor method.

3.3.1. Shunt inductor

The configuration of this method is shown in Fig. 12. In case a cell is detected to have a higher voltage than the other ones of the pack, the inductor is alternately set in parallel [95] with the cell (the cell is shunted by the inductor), activating the corresponding switches of the cell, and with the whole pack, activating the switches SWa and SWb in the figure, with the aim of transferring the extra energy from the imbalanced cell to the pack.

The average inductor current when a cell is being balanced is

$$I_L = \frac{1}{2}\left(\frac{V_{\mathrm{cell}_i}D^2 - V_{\mathrm{Bat}}(1-D)^2}{Lf_{\mathrm{sw}}}\right), \tag{14}$$

where V_{Cell_i} is the most charged cell voltage, V_{Bat} is the voltage of the whole battery pack, D is the switching duty cycle, L is the inductance, and f_{sw} is the switching frequency.

The power losses follow

$$P_{\mathrm{loss}} = I_L^2 2R_{\mathrm{sw}} + I_L^2 R_L, \tag{15}$$

where P_{loss} is the power loss, R_{sw} is the on-resistance of the switch, and R_L is the internal resistance of the inductor.

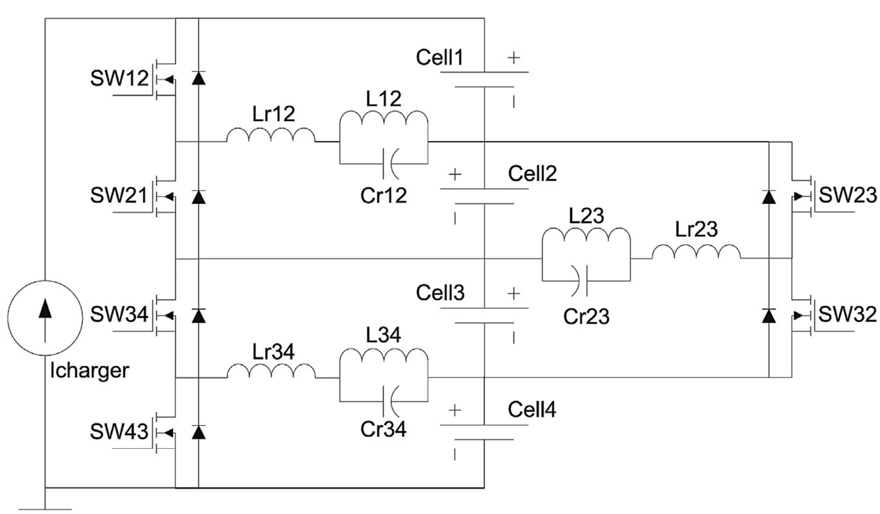

Fig. 11. QuasiResonant converter method.

This method is good for high power applications, but it is very slow since only one cell is being balanced at every instant.

3.3.2. Boost shunting

When imbalance is detected, the switch associated with the highest voltage cell together with the SWr switch (in Fig. 13) start to be controlled by a PWM signal, transferring the extra energy from the cell to the other cells in the string [96]. The topology of this method is shown in Fig. 13. The balancing module works as a boost converter.

The efficiency of the balancing process per cell is

$$P_{\text{loss}} = \frac{\sum_{i=0}^{N}\left(V_{(0)}f_{\text{sw}} + \frac{I_{\text{charger}}}{2C_{\text{Cell}_i}f_{\text{sw}}}\right)I_{charger} + \frac{V_{\text{Cell}_i}^2}{L_i^2}\frac{R}{f_{\text{sw}}^2}}{\sum_{i=0}^{N}\left(V_{i1}I_{\text{F}} - I_{\text{F}}^2R_{\text{cell}} - V_{i0}I_{\text{F}}\right)}, \tag{16}$$

where P_{loss} is total power loss, N is the number of cells in the battery pack, $V_{(0)}$ is the residual capacity of the ith-cell at the beginning of the charging, f_{sw} is the switching frequency, I_{charger} is the charging current, C_{Cell_i} is the capacitance of the cell, V_{Cell_i} is the ith-cell voltage, L_i is the inductor, R is equivalent resistance of the MOSFET, the ith-cell and the inductance, I_{F} is the discharging current, R_{Cell} is the intrinsic resistance of the ith-cell, V_{i1} is the charging voltage limit, and V_{i0} is the discharging voltage limit.

Some variations can be carried out in order to efficiently shorten the equalization time [97–100].

This method is good for high power applications, but its control complexity is high.

3.3.3. Multiple transformers

A switch in series with the secondary side of a transformer is set in parallel with each individual cell in the battery pack. The primary sides are set in parallel as shown in Fig. 14, obtaining an isolated DC/DC converter for each individual cell [45,101].

When a cell voltage exceeds the voltage threshold, the excess energy is transferred back to the battery pack by controlling its corresponding switch, and therefore its corresponding DC/DC converter. This process has two steps. In the first period, the corresponding switch is turned on and the energy is stored as a magnetic field. In the second period, and attending to Fig. 14, the corresponding switch is turned *off* and the switch SW is turned *on*, so the current flows through the primary side of the transformer and is recovered into the whole battery pack.

The equation of the average current recovered into the whole battery pack when a single cell is being balanced is similar to Equation (14).

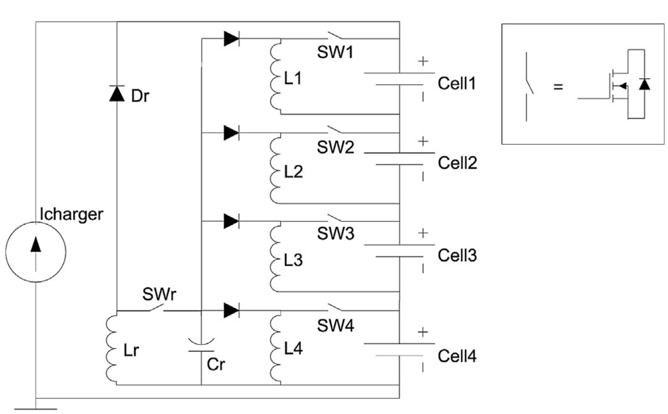

Fig. 13. Boost shunting method.

This method is good for high power applications buy it is really expensive, the cost and size are high too, and it has a high control complexity.

3.3.4. Multisecondary windings transformer

When imbalance is detected, the switch associated with the highest voltage cell is switched on and a current out of the cell into the transformer starts to flow. Because of the inductance, the amount of current rises linearly over time. As the inductance is a fixed characteristic of the transformer, the on time of the switch defines the maximum current value. The extra energy from the cell is completely stored as a magnetic field [102]. Once the switch is turned *off*, the switch SW (Fig. 15) is turned on and the transformer behavior is changed into a generator mode, so the energy is fed into the whole battery pack via the big primary winding. This method topology is shown if Fig. 15.

The average current for the ith-cell, the one which is being balanced, is

$$I_{\text{Cell}_i} = \frac{1}{2}\frac{V_{\text{Cell}_i}D^2}{L_if_{\text{sw}}}, \tag{17}$$

where I_{Cell_i} is the average ith-cell current, V_{Cell_i} is the ith-cell voltage, D is the switching duty cycle, L_i is the corresponding inductor of the ith-cell, and f_{sw} is the switching frequency.

This method can be used in high power applications but its cost and size are really high and its balancing speed is low.

3.3.5. Switched transformer

All the cells are connected to the secondary side of a transformer through a pair of switches and free-wheeling diodes as shown in Fig. 16. This method transfer the energy from the highest voltage cell through the transformer into the battery pack [103–105] by activating the corresponding cell switches. It is carried out in two

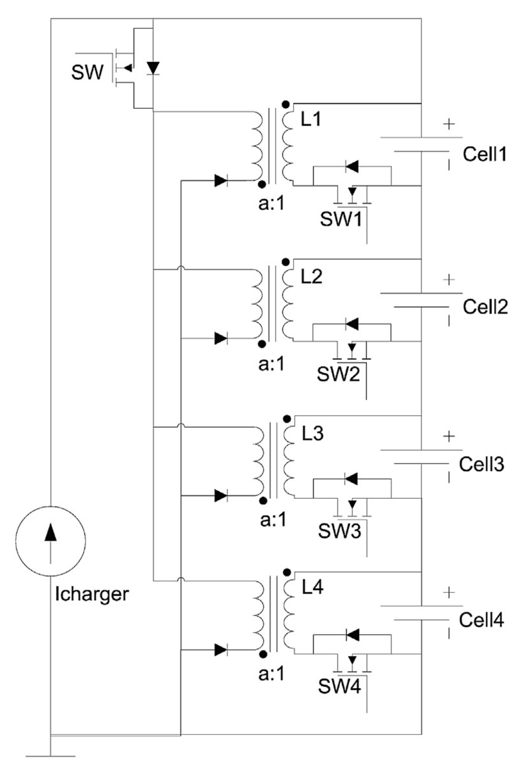

Fig. 14. *Cell to pack* multiple transformers method.

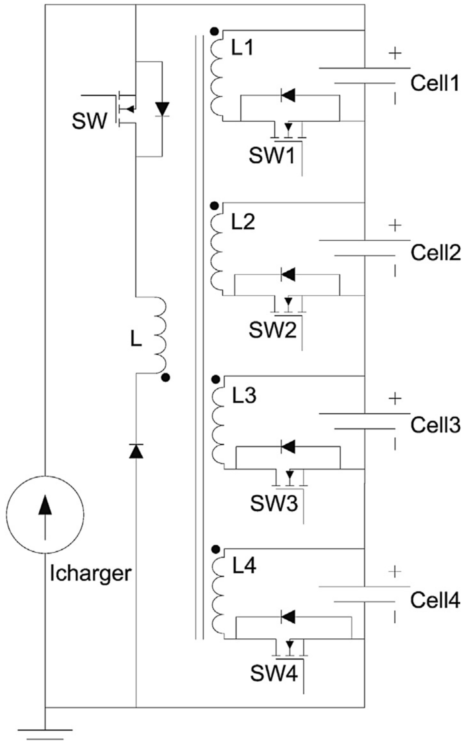

Fig. 15. *Cell to pack* multisecondary windings transformer method.

steps, along the first period, the excess of energy is extracted from the cell and stored in the transformer in the form of magnetic flux by activating the corresponding switch of the cell, and in the second period the aforementioned switch is turned off and the current is recovered into the whole battery pack.

The average current for the ith-cell is similar to the one in Equation (17).

This method can be utilized in high power applications, but its cost, size, and control complexity are high, and in addition it is relatively slow.

3.4. Pack to cell

This method can be subdivided into five methods, the voltage multiplier, full-bridge converter, multiple transformer, multi-secondary windings transformer, and switched transformer ones.

3.4.1. Voltage multiplier

In this method, two states are alternated continuously since the switch is controlled by a square signal. In the first state, each cell is being discharged through the even-numbered diodes, and therefore capacitors are being charged. The variations in the cells voltages are small enough to be negligible during a single switching cycle since the capacitors have a very low capacitance. During the off period, the charger current is distributed to the capacitors and through the odd-numbered diodes to the cells, which are charged with more or less current depending on whether the cells are less or more charged with respect to the average voltage, respectively [42,106–108]. The topology is depicted in Fig. 17.

The DC equivalent circuit is built with a current source, whose current is duty controllable as $I_{\text{charger}}(1-D)$, and each cell, whose voltage is V_i, is connected to this aforementioned current source via two diodes and an equivalent resistor R_{eq_i} that follows

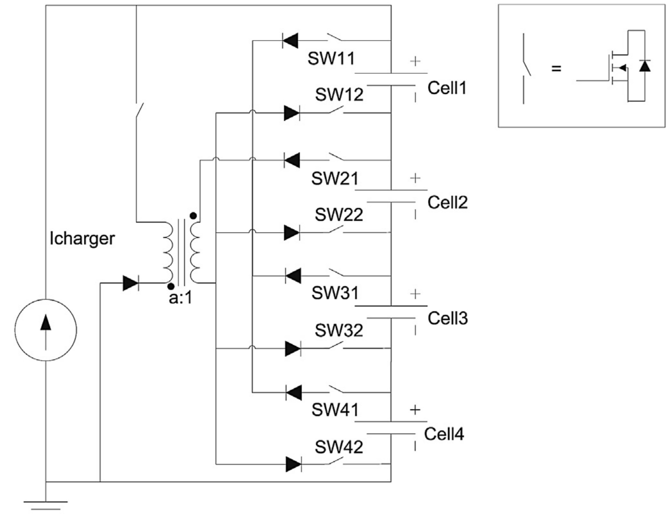

Fig. 16. *Cell to pack* switched transformer method.

$$R_{\text{eq}_i} = \frac{1}{C_i f_{\text{sw}}\left(1-\exp\left(\frac{-D}{f_{\text{sw}} C_i R_{\text{C}_i}}\right)\right)} + \frac{R_{\text{C}_i}}{1-D}, \tag{18}$$

where C_i is the capacitor connected to the ith-cell, f_{sw} is the switching frequency, D is the switching duty cycle, and R_{C_i} is the series resistance of capacitor$_i$. When cells are balanced, the current from the current source is equally distributed to the cells, in case of imbalance, the current is preferentially distributed to the cell with the lowest voltage until the balance state is reached.

According to the DC equivalent circuit, the power losses follow

$$P_{\text{loss}} = \sum_{i=1}^{N} I_{\text{Cell}_i}^2 R_{\text{eq}_i}, \tag{19}$$

where P_{loss} is the total power losses, N is the number of cells in the battery pack, and I_{Cell_i} is the balancing current for the ith-cell.

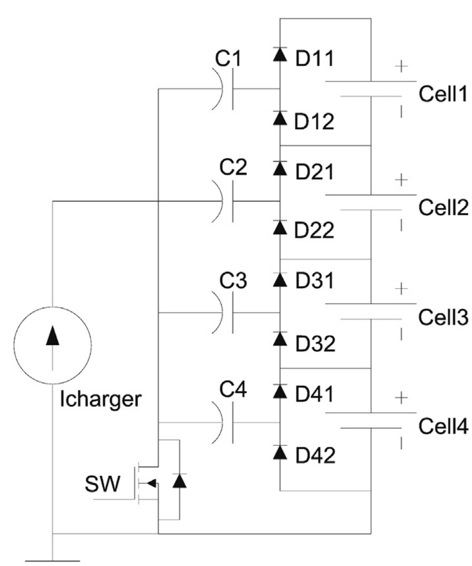

Fig. 17. Voltage multiplier method.

Equation (19) shows that the power losses tend to be large when the current is unequally distributed to the cells, since the loss is proportional to $I^2_{\mathrm{Cell}_i}$.

This balancing method can be utilized in high power applications. Its cost is relatively low and its efficiency can be high if the switching frequency is high enough to reduce R_{eq_i}, and the utilized cells have a voltage high enough to neglect the forward voltage drop of the diodes.

3.4.2. Full-bridge converter

This method is based on the full-bridge PWM converters [109–111], as shown in Fig. 18. They can be used as a AC/DC converter, which is suitable for plug-in or as a DC/DC converter. Energy is transferred from the whole battery pack to the individual cells.

The main advantages of this method are the relatively high efficiency, its easy modularity and its suitability for high power applications. Its main disadvantage is its control complexity.

3.4.3. Multiple transformers

The current from the charger is switched into the primary side of the transformer, when imbalance is detected, and so currents are induced in each of the secondaries. The secondary with the least reactance (due to a low terminal voltage on the cell) will have the most induced current. Therefore, each cell receives charging current inversely proportional to its relative SOC [43,46–48,83,112–115]. The topology utilized for this method is shown in Fig. 19.

A variation includes a switch per cell in series with the primary side. When imbalance is detected, the corresponding primary side switch SW_i of the lowest voltage cell *i*th-cell is controlled, and the rest of switches are deactivated. The balancing process is carried out in two steps. In the first step the corresponding switch SW_i is turned on and the primary current of the *i*th-cell builds up. In the second step the switch is turned off and the corresponding rectifier diode is turned on, so that the magnetizing current flows into the cell.

This balancing method is good for high power applications. The presented variation is slow as only one cell is being balanced simultaneously. Its cost is high.

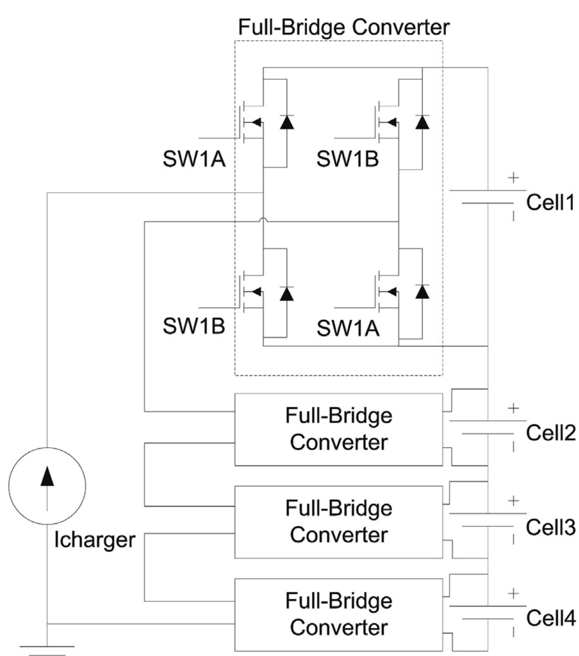

Fig. 18. Full-bridge converter method.

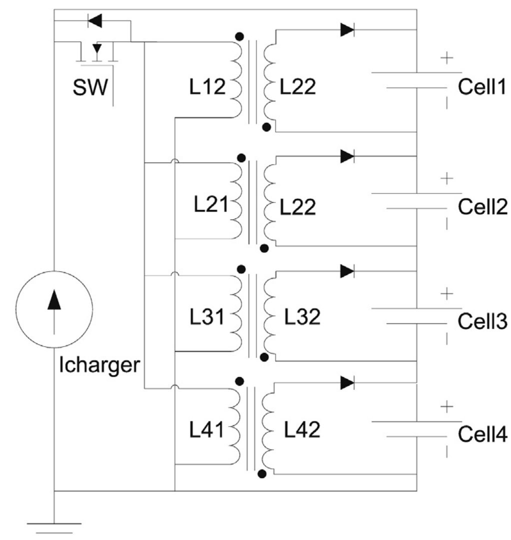

Fig. 19. *Pack to cell* multiple transformers method.

3.4.4. Multisecondary windings transformer

When imbalance is detected, the switch connected to the transformer primary winding is switched *on*, and so some energy is stored in the transformer. Then the switch is switched *off* and the energy is transferred to the secondaries of the transformer. Most of the induced current will be provided to the cell(s) with the lowest voltage (lowest reactance) via the diode(s) [14,80,102,116–123]. Fig. 20 shows a diagram of the topology of this method.

There is a variation which includes a switch per cell in series with the secondary side. Once the energy is stored in the transformer in the form of magnetic flux, the effective voltage of the target cell is the same as the cell voltage, but the effective voltage of the non-target cells is regarded as the sum of the cell voltage and the diode on-drop voltage. The difference of effective voltage causes the current unbalance and it is used for the charge equalization.

A second variation is the *ramp converter method*, which is called a ramp converter because of the shape of the primary current

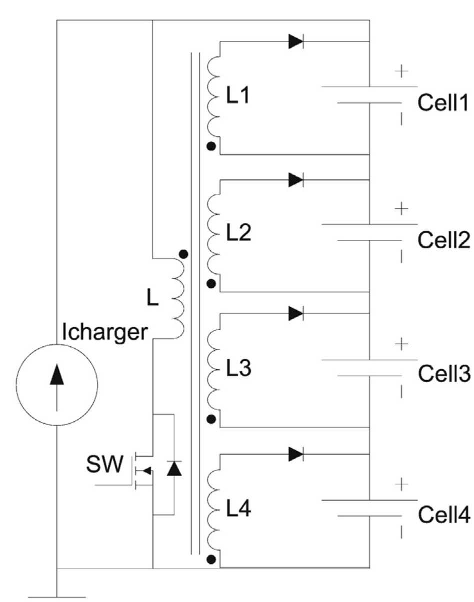

Fig. 20. *Pack to cell* multisecondary Windings Transformer method.

waveform. This circuit uses frequency modulation to regulate the average primary current, and therefore the sum of the rectified average secondary currents is also regulated. On one half cycle most of the current is supplied to the lowest voltage odd-numbered battery(s), and on the other half cycle most of the current goes to the lowest voltage even-numbered battery(s) [124,125]. This method only requires one secondary winding for each pair of batteries instead of one per battery.

This method presents high cost, size and control complexity.

3.4.5. Switched transformer

This method is similar to the multisecondary windings transformer. The difference is that this method uses only one switched transformer to transfer the energy from the whole battery pack to the lowest voltage cell through an array of switches, which selects the target cell that has to be equalized [43,46,49,80,83,126]. The topology is shown in Fig. 21.

High cost, size and control complexity are the main characteristics of this method.

3.5. Cell to pack to cell

This methods can be divided into two categories. The first group deals with the shared methods which transfer the energy from the most charged cells to a tank and from the tank to the least charged ones in the battery pack, regardless of whether the cells are adjacent or not. Shared methods are grouped into three main groups, which are PWM controlled converter, single switched capacitor, and single switched inductor.

The second group of methods are the *distributed methods* that allow the cell to pack equalization, in case the cell to be equalized has a higher voltage than the reference one (the reference voltage is usually the average or the threshold), and the pack to cell equalization in case the cell to be equalized has a lower voltage than the reference one. Distributed methods are grouped into three main groups, which are bidirectional multiple transformer, bidirectional multisecondary windings transformer, and bidirectional switched transformer.

3.5.1. PWM controlled converter

The cell balancing circuit is composed by buck–boost converters that connect the stack cells with a capacitor tank. Different topologies are found which carry out the same function. [127] proposes N-1 parallel converter legs, where N is the number of cells in the pack, as Fig. 22 shows. For each inverter leg, the input voltage source can be represented by a part of the stack cells and the output voltage can be represented by the remaining part of the stack cells. The balancing current values depend only on the unbalanced voltage fractions of both sides of the inductors terminals. Balancing currents flow naturally in the good directions, from where the voltage potential fraction is greater to where the voltage potential fraction is smaller to keep voltages equal. [128–130] propose a buck–boost converter per cell in the stack.

By considering that V_i is greater than V_{i+1}, the mean steady state balancing current $I_{L_{i,i+1}}$ follows

$$I_{L_{i,i+1}} = \frac{DV_i - (1-D)V_{i+1}}{DR_{\mathrm{Cell}_i} + (1-D)R_{\mathrm{Cell}_{i+1}} + R_{\mathrm{sw}} + R_{L_{i,i+1}}}, \tag{20}$$

where D is the switching duty cycle, R_{Cell_i} and $R_{\mathrm{Cell}_{i+1}}$ are the cell internal resistances, R_{sw} is the transistor static drain–source on-resistance, and $R_{L_{i,i+1}}$ is the inductor series resistance.

The control complexity of this method is high, the same as cost and size which are also high. It can be used for high power applications.

3.5.2. Single switched capacitor

This method is based on the switched capacitor. Firstly, the controller only selects the switches that parallel the highest voltage cell with the capacitor. Once the capacitor reaches the cell voltage, the controller only selects the switches that parallel the lowest voltage cell with the capacitor, transferring the excess energy from the capacitor to the cell [131,132]. Its topology is shown in Fig. 23.

Relatively low cost and high efficiency can be obtained for high power applications with this method. Slow balancing as only one cell is balanced at the same time.

3.5.3. Single switched inductor

This method is similar to the single switched capacitor, the only difference is that instead of using a capacitor, an inductor is utilized to store the energy and transfer it between the cells [133–137]. The topology is shown in Fig. 24. [138] proposes a small variation which changes the inductor by a transformer, carrying out the same idea of equalization.

The transferred energy E_{trans} is

$$E_{\mathrm{trans}} = \frac{1}{2}\frac{V_i D^2}{L f_{\mathrm{sw}}^2}, \tag{21}$$

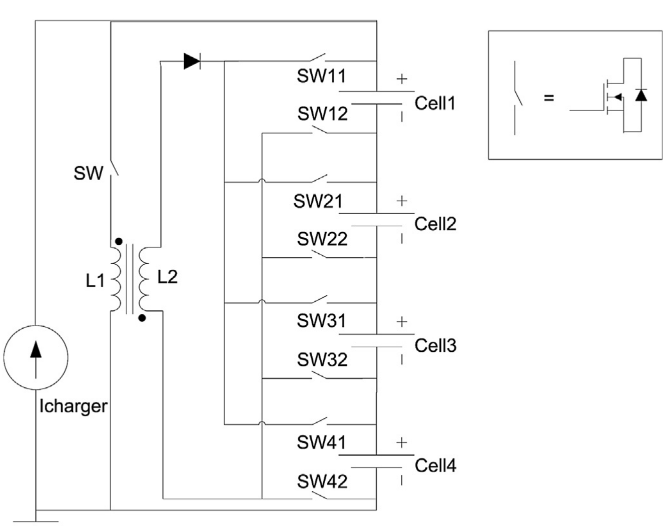

Fig. 21. *Pack to cell* switched transformer method.

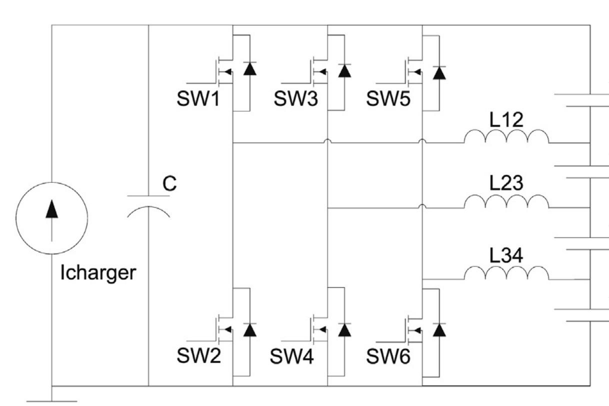

Fig. 22. *Cell to pack to cell* PWM controlled converter method.

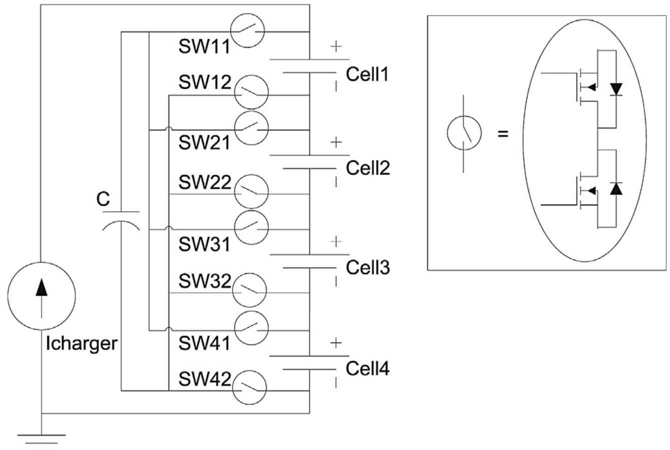

Fig. 23. Single switched capacitor method.

where V_i is the most charged cell, D is the duty cycle, L is the inductance, and f_{sw} is the switching frequency.

Similar advantages and disadvantages can be obtained compared to the *single switched capacitor* method.

3.5.4. Bidirectional multiple transformers

This method allows transferring the energy from each stack cell to the main battery bus and vice versa [45,139–141]. During charging the individual cell voltages are regulated by transferring the excess energy to the battery bus. During discharging, the energy can be transferred from the battery pack to the weak cells. The topology is shown in Fig. 25.

This method combines the different advantages of the *multiple transformers method* of the *cell to pack* and *pack to cell* groups.

3.5.5. Bidirectional multisecondary windings transformer

Each cell is in parallel with a switch in series with an inductor (the secondary side of a multisecondary windings transformer), as shown in Fig. 26. When imbalance is detected, this method allows different control types. The first control type lets the energy to be transferred from the pack to the weak cell(s) by firstly activating the switch of the primary side, and then turning it *off* and activating the corresponding switches of the target cell(s). Another control allows the energy transfer from the most charged cell (when it becomes overcharged) to the rest of the stack cells, by activating the corresponding switch of the most charged cell to transfer the energy to the primary side of the transformer (it works as an inductor tank) and as a result, the energy is transferred from that cell to other cells with most of the energy directed to the lowest voltage one, since the current absorbed by each cell is directly proportional

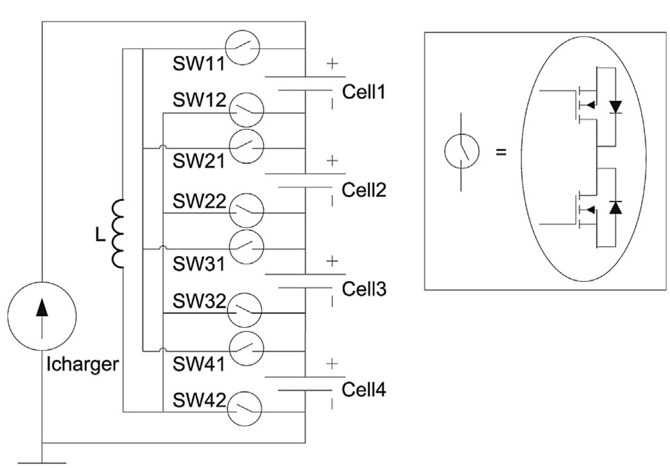

Fig. 24. Single switched inductor method.

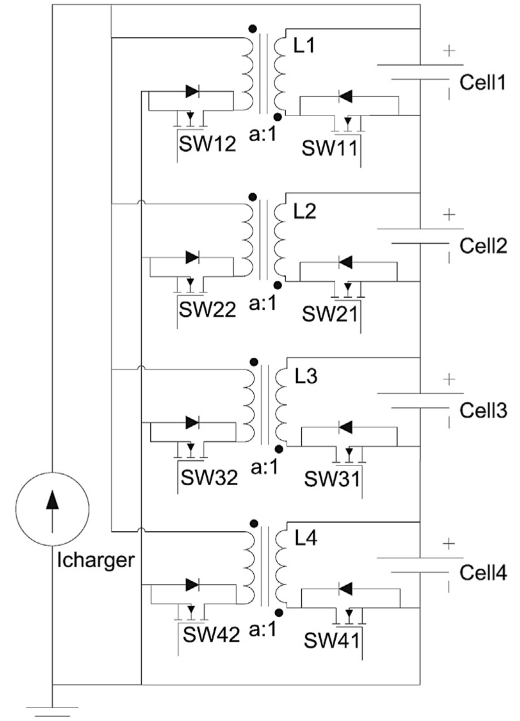

Fig. 25. Bidirectional multiple transformers method.

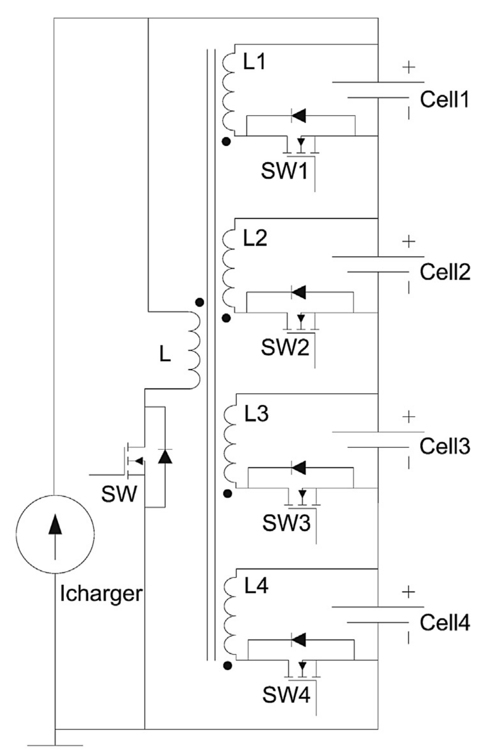

Fig. 26. Bidirectional multisecondary windings transformer method.

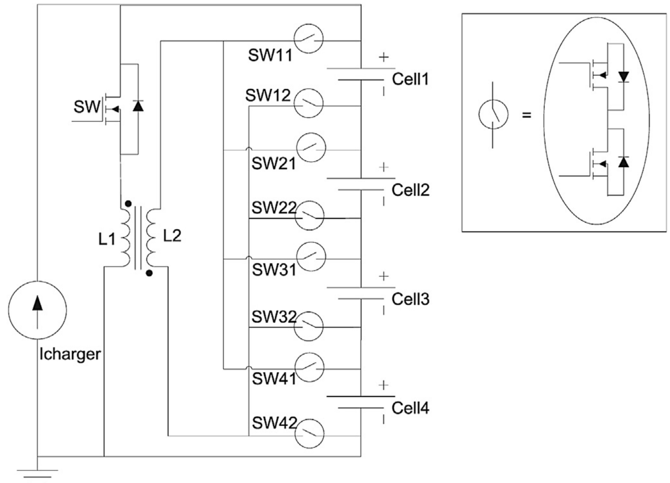

Fig. 27. Bidirectional switched transformer method.

to the voltage difference between its terminal voltage and the healthy module terminal voltage. The least charged cell accept more current compared to other cells [102,142,143]. This second control type can be implemented using a similar topology that eliminates the primary inductor and transfer the energy directly between cells, as described in Refs. [144–147].

3.5.6. *Bidirectional switched transformer*

A single transformer is utilized to transfer the energy from the most charged cell to the pack, or from the pack to the weakest cell (the least charged one), selecting the corresponding switches [148–154]. A basic diagram of the topology is shown in Fig. 27.

3.6. *Comparison*

In this section, all of the active balancing methods are compared and presented in Table 1. T represents the balancing nature, which can be ST (Shunting), SL (Shuttling) or EC (Energy conversion). Components defines what components are utilized and the number of them. Finally, twelve parameters are analyzed and used for comparison between the different methods, using a numeric scale where 1 is the minimum value and 3 the maximum one for each parameter, the average of the parameters for each method is obtained and presented as the Total. A comparison can be carried out based on Total, and as it can be seen the *switch capacitor* and the *double-tiered switching capacitor* are the ones with the highest average value. The total average of the analyzed parameters has been calculated by using the same

Table 1
Classification of active balancing methods.

*	T	Components					P1	P2	P3	P4	P5	P6	P7	P8	P9	P10	P11	P12	Total
		SW	R	L	C	D													
3.1.1.	ST	$4n$					3	3	1	3	3	3	2	3	3	3	3	1	2.58
3.1.2.	ST	n	n				3	1	1	1	1	3	1	3	2	3	3	1	1.92
3.1.3.	ST	n					3	1	1	1	1	3	2	3	3	3	3	1	2.08
3.2.1.	SL	$2n$			$n-1$		3	3	3	3	3	1	2	3	2	3	3	1	2.50
3.2.2.	SL	$2n$			$2n-3$		2	3	3	3	3	2	2	3	2	3	3	1	2.50
3.2.3.	SL	$2(n-1)$		n	$n-1$		2	2	3	3	1	2	2	1	2	2	3	3	2.17
3.2.4.	SL	$2(n-1)$		$n-1$			2	2	3	3	1	2	2	1	2	2	3	3	2.17
3.2.5.	SL	$2(n-1)$		$2(n-1)$	$n-1$		1	2	3	3	1	2	2	1	1	2	3	3	2.00
3.3.1.	SL	$2(n+1)$		1		1	2	2	3	3	1	1	2	1	3	1	2	3	1.92
3.3.2.	EC	$n+1$		$n+1$	1	$n+1$	2	2	3	3	1	2	2	1	2	2	3	3	2.17
3.3.3.	EC	n		$2n$		n	1	1	3	3	1	2	2	1	1	3	2	2	1.83
3.3.4.	EC	n		$n+1$		1	1	1	3	3	1	1	2	1	1	1	2	3	1.67
3.3.5.	EC	$2n$		2		$2n+1$	1	1	3	3	1	1	2	1	1	2	2	3	1.75
3.4.1.	SL	1			n	$2n$	3	3	3	1	1	2	2	3	2	3	1	2	2.17
3.4.2.	EC	$4n$					1	3	3	3	1	3	2	2	2	3	3	3	2.42
3.4.3.	EC	1		$2n$		n	1	1	3	1	1	2	2	3	1	3	2	2	1.83
3.4.4.	EC	1		$n+1$		n	1	1	3	1	1	2	2	3	1	1	2	3	1.75
3.4.5.	EC	$2n+1$		2		1	1	1	3	1	1	1	2	1	1	2	2	3	1.67
3.5.1.	EC	$2(n-1)$		$n-1$	1		1	2	3	3	1	2	2	1	2	3	2	2	2.00
3.5.2.	SL	$4n$			1		3	3	3	3	3	1	2	1	3	1	3	2	2.33
3.5.3.	SL	$4n$		1			2	2	3	3	3	1	2	1	3	1	3	2	2.17
3.5.4.	EC	$2n$		$2n$			1	1	3	3	1	2	2	1	1	3	2	2	1.83
3.5.5.	EC	$n+1$		$n+1$			1	1	3	3	1	2	2	1	1	1	2	3	1.75
3.5.6.	EC	$4n+1$		2			1	1	3	3	1	2	2	1	1	2	2	3	1.83

*Every analyzed method is defined by its section number.
Parameters of comparison
T. Balancing nature: ST (Shunting), SL (Shuttling), EC (Energy Conversion).
Components. S (Switches), R (Resistors), L (Inductors), C (Capacitors), D (Diodes).
P1. Cost (1: expensive, 3: cheap).
P2. Efficiency (1: low, 3: high).
P3. Application (1: only allows low power, 3: allows high power).
P4. Charge/Discharge type (1: unidirectional, 3: bidirectional).
P5. Best effective period (1: one effective mode, 3: both modes are effective).
P6. Speed (1: low, 3: high).
P7. Implementation (1: low, 3: high).
P8. Complexity (1: high, 3: low).
P9. Size (1: big, 3: small).
P10. Modular (1: difficult, 3: easy).
P11. Switch Voltage Stress (1: high, 3: low).
P12. Switch Current Stress (1: high, 3: low).

weight for each of them, however, their weight should be modified according to the application. *Cell bypass* methods are the cheapest ones, and in addition they are easily modularized and controlled. *Cell to cell* methods are more efficient and can be used in high power applications. *Cell to pack*, *pack to cell*, and *cell to pack to cell* methods allow low switch voltage and current stress even in high power applications.

4. Conclusions

With the aim of solving the numerous problems which can occur in case of battery imbalance, a large number of battery equalization methods are available. It can make the selection difficult whenever a battery equalization system has to be applied to a battery pack. In order to make the decision easier, a complete overview of the active balancing methods is presented in this paper. A final table summarizes and compares their main characteristics, introducing a good resource to analyze (by adjusting the parameters weights depending on the application) and defining the most suitable method according to the application. By setting the same weight for every parameter, as it is shown in Table 1, the *switched capacitor* and the *double-tiered switching capacitor* methods are the best option according to the obtained results.

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References

[1] P. Sveum, R. Kizilel, M. Khader, S. Al-Hallaj, in: Proc. IEEE Vehicle Power and Propulsion Conf. VPPC, 2007, pp. 493–497.
[2] S. D'Arco, L. Piegari, P. Tricoli, in: Electrical Systems for Aircraft, Railway and Ship Propulsion (ESARS), 2012, pp. 1–6.
[3] Y.-H. Hsieh, T.-J. Liang, S.-M. Chen, W.-Y. Horng, Y.-Y. Chung, IEEE Transactions on Power Electronics 28 (2013) 5927–5939.
[4] M. Dubarry, N. Vuillaume, B.Y. Liaw, Journal of Power Sources 186 (2009) 500–507.
[5] J. Shim, K.A. Striebel, Journal of Power Sources 122 (2003) 188–194.
[6] M. Uno, K. Tanaka, IEEE Transactions on Vehicular Technology 60 (2011) 1505–1515.
[7] D.D. Friel, in: Electric and Hybrid Vehicles, Elsevier, Amsterdam, 2010, pp. 493–515.
[8] Y. Zheng, L. Lu, X. Han, J. Li, M. Ouyang, Journal of Power Sources 226 (2013) 33–41.
[9] B. T. Kuhn, G. E. Pitel, P. T. Krein, in: Proc. IEEE Conf. Vehicle Power and Propulsion.
[10] M. Broussely, M. Perelle, J. McDowall, G. Sarre, J. Martaeng, in: Proc. INTELEC Twenty-second Int. Telecommunications Energy Conf., pp. 194–201.
[11] H. Qian, J. Zhang, J.-S. Lai, W. Yu, IEEE Transactions on Power Electronics 26 (2011) 886–896.
[12] G. Landrum, T. Stuart, W. Zhu, in: Oceans, 2008, pp. 1–6.
[13] W.C. Lee, D. Drury, IEEE Transactions on Power Electronics 28 (2013) 5949–5959.
[14] N. Kutkut, H. Wiegman, D. Divan, D. Novotny, IEEE Transactions on Industry Applications 35 (1999) 28–35.
[15] B.C. Jaemoon Lee, Oanyong Nam, Journal of Power Sources 174 (2007) 9–15.
[16] L. Lu, X. Han, J. Li, J. Hua, M. Ouyang, Journal of Power Sources 226 (2013) 272–288.
[17] T.A. Stuart, W. Zhu, Journal of Power Sources 196 (2011) 458–464.
[18] R. Ugle, Y. Li, A. Dhingra, Journal of Power Sources 223 (2013) 293–305.
[19] J. Li, H. Lu, Z. Yang, F. Pei, in: International Conference on Transportation, Mechanical, and Electrical Engineering (TMEE), 2011, pp. 966–969.
[20] P. Li, Y. Pan, Y. Ma, Q. Qin, in: International Conference on Electronic and Mechanical Engineering and Information Technology (EMEIT), vol. 1, 2011, pp. 141–144.
[21] M. Einhorn, W. Guertlschmid, T. Blochberger, R. Kumpusch, R. Permann, F. Conte, C. Kral, J. Fleig, IEEE Transactions on Vehicular Technology 60 (2011) 4227–4237.
[22] S. Lee, J. Kim, J. Lee, B. Cho, Journal of Power Sources 185 (2008) 1367–1373.
[23] M. Broussely, S. Herreyre, P. Biensan, P. Kasztejna, K. Nechev, R. Staniewicz, Journal of Power Sources 97-98 (2001) 13–21.
[24] A. Hande, T. Stuart, Journal of Power Sources 138 (2004) 327–339.
[25] C.-C. Hua, Y.-H. Fang, in: IEEE 10th International Conference on Power Electronics and Drive Systems (PEDS), 2013, pp. 221–225.
[26] W. Bentley, in: Twelfth Annual Battery Conference on Applications and Advances, 1997, pp. 223–226.
[27] H.-S. Park, C.-H. Kim, K.-B. Park, G.-W. Moon, J.-H. Lee, IEEE Transactions on Vehicular Technology 58 (2009) 3216–3223.
[28] S. Chen, C.-C. Chen, H.-P. Huang, C.-C. Hwu, in: 9th World Congress on Intelligent Control and Automation (WCICA), 2011, pp. 468–473.
[29] S. Hung, D. Hopkins, C. Mosling, IEEE Transactions on Industrial Electronics 40 (1993) 96–104.
[30] P. Krein, R. Balog, in: 24th Annual International Telecommunications Energy Conference, INTELEC, 2002, pp. 516–523.
[31] D. Hopkins, C. Mosling, S. Hung, IEEE Transactions on Industry Applications 29 (1993) 363–368.
[32] S. Munwaja, B. Tanboonjit, N. H. Fuengwarodsakul, in: Proc. 9th Int. Electrical Engineering/Electronics, Computer, Telecommunications and Information Technology (ECTI-CON) Conf., pp. 1–4.
[33] Y. Barsukov, in: Portable Power Design Seminar – Texas Instruments, 2006.
[34] J.D. Li, Z.T. Yong, Z.F. Hui, X. Peng, in: 6th International Forum on Strategic Technology (IFOST), vol. 1, 2011, pp. 265–268.
[35] P. Cassani, S. Williamson, IEEE Transactions on Industrial Electronics 57 (2010) 3956–3962.
[36] L. Wang, L. Wang, C. Liao, J. Liu, in: IEEE Vehicle Power and Propulsion Conference, VPPC '09, 2009, pp. 1788–1791.
[37] K. Zhiguo, C. Shukang, in: IEEE Vehicle Power and Propulsion Conference, VPPC '08, 2008, pp. 1–5.
[38] T. Stuart, W. Zhu, in: IEEE Vehicle Power and Propulsion Conference, VPPC '09, 2009, pp. 175–180.
[39] T. Stuart, W. Zhu, IEEE Aerospace and Electronic Systems Magazine 24 (2009b) 27–31.
[40] J. Kim, J. Shin, C. Chun, B.H. Cho, IEEE Transactions on Power Electronics 27 (2012) 411–424.
[41] J.-H. Kim, J.-W. Shin, C.-Y. Jeon, B.-H. Cho, in: International Power Electronics Conference (IPEC), 2010, pp. 1174–1179.
[42] M. Uno, K. Tanaka, IEEE Transactions on Industrial Electronics, in press, early access.
[43] J. Cao, N. Schofield, A. Emadi, in: Proc. IEEE Vehicle Power and Propulsion Conf., VPPC '08, pp. 1–6.
[44] D. Hopkins, C. Mosling, S. Hung, in: Sixth Annual Applied Power Electronics Conference and Exposition, 1991, APEC '91, Conference Proceedings, 1991, pp. 493–498.
[45] N. Kutkut, D. Divan, in: 18th International Telecommunications Energy Conference, INTELEC '96, 1996, pp. 514–521.
[46] M. Daowd, N. Omar, P. Van Den Bossche, J. Van Mierlo, in: Proc. IEEE Vehicle Power and Propulsion Conf. (VPPC), pp. 1–7.
[47] K. Zhi-Guo, Z. Chun-Bo, L. Ren-Gui, C. Shu-Kang, in: Proc. 37th IEEE Power Electronics Specialists Conf. PESC '06, pp. 1–6.
[48] X. Wei, B. Zhu, in: 9th International Conference on Electronic Measurement Instruments, ICEMI '09, 2009, pp. 2-498–2-502.
[49] C.-H. Kim, M.-Y. Kim, H.-S. Park, G.-W. Moon, IEEE Transactions on Power Electronics 27 (2012) 3764–3774.
[50] M. Brandl, H. Gall, M. Wenger, V. Lorentz, M. Giegerich, F. Baronti, G. Fantechi, L. Fanucci, R. Roncella, R. Saletti, S. Saponara, A. Thaler, M. Cifrain, W. Prochazka, in: Proc. Design, Automation & Test in Europe Conf. & Exhibition (DATE), pp. 971–976.
[51] B. Dong, Y. Han, in: IEEE Energy Conversion Congress and Exposition (ECCE), 2011, pp. 928–934.
[52] F. Baronti, G. Fantechi, R. Roncella, R. Saletti, in: IEEE International Symposium on Industrial Electronics (ISIE), 2012, pp. 1330–1335.
[53] T. Kim, W. Qiao, L. Qu, in: Proc. Twenty-Seventh Annual IEEE Applied Power Electronics Conf. and Exposition (APEC), pp. 2259–2264.
[54] A. Manenti, A. Abba, A. Merati, S. Savaresi, A. Geraci, IEEE Transactions on Industrial Electronics 58 (2011) 4314–4322.
[55] H. Shibata, S. Taniguchi, K. Adachi, K. Yamasaki, G. Ariyoshi, K. Kawata, K. Nishijima, K. Harada, in: 4th IEEE International Conference on Power Electronics and Drive Systems, 2001, Proceedings, vol. 2, 2001, pp. 508–511.
[56] V. Teofilo, L. Merritt, R. Hollandsworth, IEEE Aerospace and Electronic Systems Magazine 12 (1997) 30–36.
[57] D. Xu, L. Wang, J. Yang, in: International Conference on Electrical and Control Engineering (ICECE), 2010, pp. 4106–4109.
[58] V. Teofilo, L. Merritt, R. Hollandsworth, in: Twelfth Annual Battery Conference on Applications and Advances, 1997, pp. 227–231.
[59] L. Hu, M.-L. Zhao, X.-B. Wu, J.-N. Lou, in: 10th IEEE International Conference on Solid-state and Integrated Circuit Technology (ICSICT), 2010, pp. 339–341.
[60] B. Tsenter, M. Golod, Energy Transfer and Equalization in Rechargeable Lithium Batteries, Mar. 21, 2000.
[61] W.H. DeLuca, F. H Jr., G.H. Gelb, B. Berman, L.W. Moede, System and Method for Charging Electrochemical Cells in Series, Dec. 9, 1980.
[62] A. Govindaraj, S. Lukic, A. Emadi, A novel scheme for optimal paralleling of batteries and ultracapacitors, in: IEEE Energy Conversion Congress and Exposition, ECCE 2009, 2009, pp. 1410–1416.

[63] J.W. Kimball, B.T. Kuhn, P.T. Krein, in: Proc. IEEE Vehicle Power and Ropulsion Conf. VPPC, 2007, pp. 323–327.
[64] R. Lu, C. Zhu, L. Tian, Q. Wang, IEEE Transactions on Magnetics 43 (2007) 254–258.
[65] J. Kimball, P. Krein, in: Twentieth Annual IEEE Applied Power Electronics Conference and Exposition, APEC 2005, vol. 3, 2005, pp. 1473–1477.
[66] G. Kobzev, in: Modern Techniques and Technology, MTT 2000. Proceedings of the VI International Scientific and Practical Conference of Students, Post-graduates and Young Scientists, 2000, pp. 57–59.
[67] S. West, P. Krein, in: Twenty-second International Telecommunications Energy Conference, INTELEC, 2000, pp. 439–446.
[68] C. Pascual, P. Krein, in: Twelfth Annual Applied Power Electronics Conference and Exposition, 1997, APEC '97 Conference Proceedings, vol. 2, 1997, pp. 848–854.
[69] A. Baughman, M. Ferdowsi, in: Vehicle Power and Ropulsion Conference, VPPC '06, IEEE, 2006, pp. 1–6.
[70] A. Baughman, M. Ferdowsi, in: IEEE Conference Vehicle Power and Propulsion, 2005, pp. 109–113.
[71] A. Baughman, M. Ferdowsi, IEEE Transactions on Industrial Electronics 55 (2008) 2277–2285.
[72] J. Yan, Z. Cheng, G. Xu, H. Qian, Y. Xu, in: IEEE 72nd Vehicular Technology Conference Fall (VTC 2010-Fall), 2010, pp. 1–7.
[73] Y.-S. Lee, M.-W. Cheng, IEEE Transactions on Industrial Electronics 52 (2005) 1297–1307.
[74] Y.-S. Lee, C.-Y. Duh, G.-T. Chen, S.-C. Yang, in: IEEE 36th Power Electronics Specialists Conference, PESC '05, 2005, pp. 765–771.
[75] Y.-S. Lee, C.-W. Jao, in: IEEE International Conference on Systems, Man and Cybernetics, vol. 5, 2003, pp. 4431–4438.
[76] T.H. Phung, J. Crebier, A. Chureau, A. Collet, T. Van Nguyen, in: Applied Power Electronics Conference and Exposition (APEC), Twenty-sixth Annual IEEE, 2011, pp. 1374–1381.
[77] Journal of Power Sources 63 (1996) 299.
[78] Y. Gong, T. Tang, in: Proc. Int. Power Electronics, Electrical Drives, Automation and Motion (SPEEDAM) Symp., pp. 347–352.
[79] C.-H. Lin, C.-M. Wang, H.-Y. Chao, M.-H. Hung, in: IEEE Third International Conference on Sustainable Energy Technologies (ICSET), 2012, pp. 229–234.
[80] D. Cadar, D. Petreus, T. Patarau, R. Etz, in: International Conference on Power Engineering, Energy and Electrical Drives (POWERENG), 2011, pp. 1–6.
[81] J. Ewanchuk, D. Yague, J. Salmon, in: IEEE Energy Conversion Congress and Exposition (ECCE), 2011, pp. 2908–2915.
[82] C.-H. Lin, H.-Y. Chao, C.-M. Wang, M.-H. Hung, in: TENCON 2011 - 2011 IEEE Region 10 Conference, pp. 863-867.
[83] D. Cadar, D. Petreus, T. Patarau, in: 33rd International Spring Seminar on Electronics Technology (ISSE), 2010, pp. 290–293.
[84] M. Chen, Z. Zhang, Z. Feng, J. Chen, Z. Qian, in: Twenty-fourth Annual IEEE Applied Power Electronics Conference and Exposition, APEC 2009, 2009, pp. 186–189.
[85] J. Zhao, J. Jiang, L. Niu, in: The Fifth International Conference on Power Electronics and Drive Systems, PEDS 2003, vol. 2, 2003, pp. 853–857.
[86] K. Nishijima, H. Sakamoto, K. Harada, in: Proc. IEEE 31th Annual Power Electronics Specialists Conference, vol. 1, pp. 517–520.
[87] R. Ling, Y. Dong, H. Yan, M. Wu, Y. Chai, in: Proc. 7th Int. Power Electronics and Motion Control Conf. (IPEMC), vol. 4, pp. 2631–2635.
[88] S.-H. Park, K.-B. Park, H.-S. Kim, G.-W. Moon, M.-J. Youn, IEEE Transactions on Power Electronics 27 (2012) 2900–2911.
[89] T. Hoon Kim, N. Ju Park, R. Young Kim, D. Seok Hyun, in: Proc. Twenty-seventh Annual IEEE Applied Power Electronics Conf. and Exposition (APEC), pp. 2590–2595.
[90] Y.-S. Lee, C.-E. Tsai, Y.-P. Ko, M.-W. Cheng, in: International Power Electronics Conference (IPEC), 2010, pp. 2722–2728.
[91] M.-W. Cheng, Y.-S. Lee, R.-H. Chen, W.-T. Sie, in: 31st International Telecommunications Energy Conference, INTELEC 2009, 2009, pp. 1–6.
[92] Y.-S. Lee, G.-T. Cheng, IEEE Transactions on Power Electronics 21 (2006) 1213–1224.
[93] G. Hua, E. Yang, Y. Jiang, F. Lee, in: PESC '93 Record, 24th Annual IEEE Power Electronics Specialists Conference, 1993, pp. 538–544.
[94] M. Isaacson, R. Hollandsworth, P. Giampaoli, F. Linkowsky, A. Salim, V. Teofilo, in: The Fifteenth Annual Battery Conference on Applications and Advances, 2000, pp. 193–198.
[95] G. Jin-hui, J. Li-feng, L. Ying-ying, T. Jing, in: International Conference on Electrical and Control Engineering (ICECE), 2010, pp. 4403–4405.
[96] C. Moo, Y. Hsieh, I. Tsai, IEEE Transactions on Aerospace and Electronic Systems 39 (2003) 704–710.
[97] Y.-H. Zhang, J.-G. Li, J. Lin, J.-F. Ge, in: International Conference on Artificial Intelligence and Computational Intelligence, AICI '09, vol. 1, 2009, pp. 553–557.
[98] C. Moo, Y. Hsieh, I. Tsai, J. Cheng, IEEE Proceedings on Electric Power Applications 150 (2003) 501–505.
[99] Y. Hsieh, C. Moo, I. Tsai, J. Cheng, in: IEEE International Conference on Industrial Technology, IEEE ICIT '02, vol. 1, 2002, pp. 444–449.
[100] W.-l. Chen, S.-R. Cheng, in: Generation, Transmission Distribution, IET, vol. 7, 2013.
[101] H.-S. Park, C.-E. Kim, G.-W. Moon, J.-H. Lee, J.K. Oh, in: IEEE Power Electronics Specialists Conference, PESC 2007, 2007, pp. 273–279.
[102] C. Bonfiglio, W. Roessler, in: VPPC '09, IEEE Vehicle Power and Propulsion Conference, 2009, pp. 304–309.
[103] A. Imtiaz, F. Khan, H. Kamath, in: Twenty-sixth Annual IEEE Applied Power Electronics Conference and Exposition (APEC), 2011, pp. 792–799.
[104] J.-W. Shin, G.-S. Seo, C.-Y. Chun, B.-H. Cho, in: International Power Electronics Conference (IPEC), 2010, pp. 1180–1184.
[105] A. Imtiaz, F. Khan, IEEE Transactions on Power Electronics 28 (2013) 5960–5975.
[106] M. Uno, K. Tanaka, in: IEEE 8th International Conference on Power Electronics and ECCE Asia (ICPE ECCE), 2011, pp. 2985–2989.
[107] M. Uno, K. Tanaka, in: IEEE Ninth International Conference on Power Electronics and Drive Systems (PEDS), 2011, pp. 1158–1165.
[108] M. Uno, A. Kukita, K. Tanaka, in: IPEC Conference Proceedings, 2010, pp. 538–543.
[109] C.-M. Young, N.-Y. Chu, L.-R. Chen, Y.-C. Hsiao, C.-Z. Li, IEEE Transactions on Industrial Electronics 60 (2013) 1972–1978.
[110] P. Chanhom, S. Sirisukprasert, N. Hatti, in: Proc. 9th Int. Electrical Engineering/Electronics, Computer, Telecommunications and Information Technology (ECTI-CON) Conf., pp. 1–4.
[111] L. Maharjan, S. Inoue, H. Akagi, J. Asakura, IEEE Transactions on Power Electronics 24 (2009) 1628–1636.
[112] C.-H. Kim, M.-Y. Kim, G.-W. Moon, in: IEEE Vehicle Power and Propulsion Conference (VPPC), 2012, pp. 327–332.
[113] H.-S. Park, C.-E. Kim, C.-H. Kim, G.-W. Moon, J.-H. Lee, IEEE Transactions on Industrial Electronics 56 (2009) 1464–1476.
[114] C.-H. Kim, H.-S. Park, C.-E. Kim, G.-W. Moon, J.-H. Lee, J.K. Oh, in: 7th International Conference on Power Electronics, ICPE '07, 2007, pp. 795–800.
[115] H.-S. Park, C.-E. Kim, G.-W. Moon, J.-H. Lee, J.K. Oh, in: IEEE Power Electronics Specialists Conference, PESC 2007, 2007, pp. 266–272.
[116] P. Mishra, A. Pandey, J. Joshi, Solar Energy Materials and Solar Cells 44 (1996) 11–24.
[117] H.-S. Park, C.-H. Kim, G.-W. Moon, in: IEEE International Conference on Sustainable Energy Technologies, ICSET 2008, 2008, pp. 558–563.
[118] W.-S. Jwo, W.-L. Chien, in: Conference Record of the 2007 IEEE Industry Applications Conference, 42nd IAS Annual Meeting, 2007, pp. 1076–1081.
[119] G. Chen, Z. Huang, Z. Zhong, in: International Conference on Electric Information and Control Engineering (ICEICE), 2011, pp. 1902–1905.
[120] M.-Y. Kim, C.-H. Kim, S.-Y. Cho, G.-W. Moon, in: IEEE 8th International Conference on Power Electronics and ECCE Asia (ICPE ECCE), 2011, pp. 310–317.
[121] X. Wei, X. Zhao, D. Haifeng, in: IEEE Vehicle Power and Propulsion Conference, VPPC '09, 2009, pp. 1654–1656.
[122] A. Xu, X. Liu, S. Xie, in: IEEE International Conference on Industrial Technology, ICIT 2009, 2009, pp. 1–6.
[123] A. Xu, S. Xie, X. Liu, IEEE Transactions on Vehicular Technology 58 (2009b) 3981–3987.
[124] M. Tang, T. Stuart, IEEE Transactions on Aerospace and Electronic Systems 36 (2000) 201–211.
[125] T. Gottwald, Z. Ye, T. Stuart, IEEE Transactions on Aerospace and Electronic Systems 33 (1997) 307–312.
[126] C.-H. Kim, H.-S. Park, G.-W. Moon, in: IEEE Power Electronics Specialists Conference, PESC 2008, 2008, pp. 992–997.
[127] F. Mestrallet, L. Kerachev, J. Crebier, A. Collet, in: Proc. Twenty-seventh Annual IEEE Applied Power Electronics Conf. and Exposition (APEC), pp. 369–376.
[128] C.-S. Moo, K.S. Ng, Y.-C. Hsieh, IEEE Transactions on Energy Conversion 23 (2008) 701–707.
[129] W. Hong, K.-S. Ng, J.-H. Hu, C.-S. Moo, in: International Power Electronics Conference (IPEC), 2010, pp. 1568–1572.
[130] C. Moo, K. Ng, Y. Hsieh, in: International Conference on Power Electronics and Drives Systems, PEDS 2005, vol. 2, 2005, pp. 983–988.
[131] C. Speltino, A. Stefanopoulou, G. Fiengo, in: American Control Conference (ACC), 2010, pp. 5050–5055.
[132] F. Baronti, G. Fantechi, R. Roncella, R. Saletti, IEEE Transactions on Industrial Informatics 9 (2013) 1139–1147.
[133] S. Yarlagadda, I. Husain, T. Hartley, IEEE Transactions on Industry Applications (2013), 1–1.
[134] S.-H. Park, T.-S. Kim, J.-S. Park, G.-W. Moon, M.-J. Yoon, in: Twenty-fourth Annual IEEE Applied Power Electronics Conference and Exposition, APEC 2009, 2009, pp. 1246–1250.
[135] S.-H. Park, T.-S. Kim, J.-S. Park, G.-W. Moon, M.-J. Yoon, in: 7th International Conference on Power Electronics, ICPE '07, 2007, pp. 962–965.
[136] S. Yarlagadda, T. Hartley, I. Husain, in: IEEE Energy Conversion Congress and Exposition (ECCE), 2011, pp. 1188–1195.
[137] J. Yun, T. Yeo, J. Park, in: Applied Power Electronics Conference and Exposition (APEC), Twenty-eighth Annual IEEE, 2013, pp. 3301–3304.
[138] Z. Nie, C. Mi, in: IEEE Vehicle Power and Propulsion Conference, VPPC '09, 2009, pp. 78–81.

[139] G. Altemose, P. Hellermann, T. Mazz, in: IEEE Long Island Systems, Applications and Technology Conference (LISAT), 2011, pp. 1–7.
[140] C. Karnjanapiboon, K. Jirasereeamornkul, V. Monyakul, in: International Power Electronics Conference (IPEC), 2010, pp. 1185–1188.
[141] C. Karnjanapiboon, K. Jirasereeamornkul, V. Monyakul, in: IEEE International Symposium on Industrial Electronics, ISIE 2009, 2009, pp. 1504–1509.
[142] Y. Hsieh, C. Moo, W. Ou-Yang, in: International Conference on Power Electronics and Drives Systems, PEDS 2005, vol. 2, 2005, pp. 1578–1583.
[143] M. Einhorn, W. Roessler, J. Fleig, IEEE Transactions on Vehicular Technology 60 (2011) 2448–2457.
[144] S. Li, C. Mi, M. Zhang, IEEE Transactions on Industry Applications 49 (2013) 198–207.
[145] S. Li, C. Mi, M. Zhang, in: Proc. Twenty-Seventh Annual IEEE Applied Power Electronics Conf. and Exposition (APEC), pp. 2128–2133.
[146] H. Shen, W. Zhu, W. Chen, in: Asia-pacific Power and Energy Engineering Conference (APPEEC), 2010, pp. 1–4.
[147] H. Shen, W. Zhu, W. Chen, in: 9th International Conference on Electronic Measurement Instruments, ICEMI '09, 2009, pp. 4-1032–4-1037.
[148] C.-H. Kim, M.-Y. Kim, G.-W. Moon, IEEE Transactions on Power Electronics 28 (2013) 3779–3787.
[149] W. C. Lee, D. Drury, P. Mellor, in: Proc. IEEE Transportation Electrification Conf. and Expo (ITEC), pp. 1–6.
[150] C.-H. Kim, M.-Y. Kim, Y.-D. Kim, G.-W. Moon, in: IEEE 8th International Conference on Power Electronics and ECCE Asia (ICPE ECCE), 2011, pp. 304–309.
[151] M.-Y. Kim, J.-W. Kim, C.-H. Kim, S.-Y. Cho, G.-W. Moon, in: IEEE 8th International Conference on Power Electronics and ECCE Asia (ICPE ECCE), 2011, pp. 2248–2255.
[152] W.C. Lee, D. Drury, P. Mellor, in: IEEE Vehicle Power and Propulsion Conference (VPPC), 2011, pp. 1–7.
[153] C.-H. Kim, M.-Y. Kim, J.-H. Kim, G.-W. Moon, in: 31st International Telecommunications Energy Conference, INTELEC 2009, 2009, pp. 1–6.
[154] C.-H. Kim, Y.-D. Kim, G.-W. Moon, H.-S. Park, in: IEEE Energy Conversion Congress and Exposition, ECCE 2009, 2009, pp. 1812–1817.

Glossary

HEV: Hybrid Electric Vehicle
EV: Electric Vehicle
PWM: Pulse Width Modulation
$I_{charger}$: Charging/Discharging current
N: Number of cells in the battery pack
C_{Cell_i}: Cell$_i$ capacity
I_{Cell_i}: Cell$_i$ current
V_{Cell_i}: Cell$_i$ voltage
SOC: State of Charge (%)
$\Delta\eta$: Efficiency degradation
f_{sw}: Switching frequency
D: Switching Duty cycle
R_{sw_i}: Switch$_i$ on-resistance
Q_{C_i}: Capacitor stored charge
C_i: Capacitor$_i$ capacitance
R_{C_i}: Capacitor$_i$ series resistance
I_{C_i}: Capacitor$_i$ current
V_{u_i}, V_{l_i}: Upper and lower voltage cell
L_i: Inductor average current
R_L: Inductor series resistance
V_{Bat}: Battery pack voltage
P_{loss}: Total power loss
R_{eq_i}: Equivalent resistor